Investigation of atomic processes in laser produced plasmas for the short wavelength light sources

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Properties of 4d-4f transition

- Gd and Tb ions have emission through 4d-4f transitions around λ=6.5nm.
- At higher temperature, narrower emission spectrum is observed from 4d open shell (Rh- to Rb- isoelectronic sequence) ions.

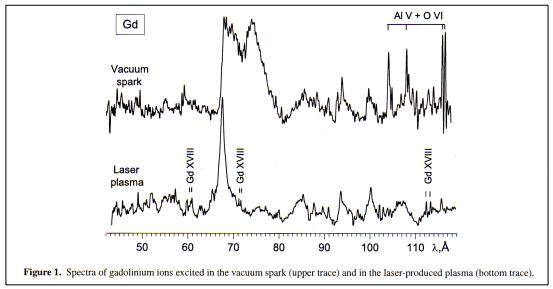


Figure 1. Spectra of gadolinium ions excited in the vacuum spark (upper trace) and in the laser-produced plasma (bottom trace).

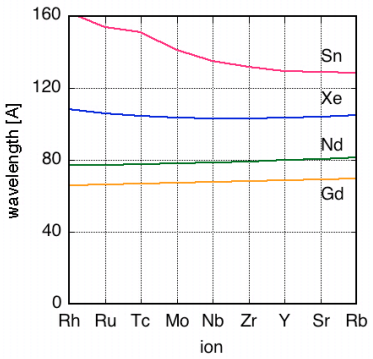
S. S. Churilov, Phys. Scr. 80, 045303 (2009).

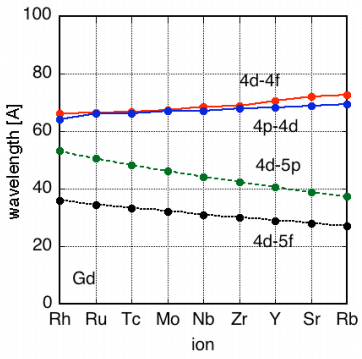
Introduction

- EUV source at λ=6.5nm is interested for future lithographic applications.
- Multiple charged ions of atomic elements with 50 ≤ Z ≤ 80 show strong emission in EUV wavelength region.
- Emission spectrum and CE from Gd and Tb LPP sources are estimated by applying the theoretical model used to investigate Sn plasmas.
- Subjects for theoretical investigation of short wavelength light sources are discussed.

Wavelength of 4d-4f + 4p-4d transition arrays

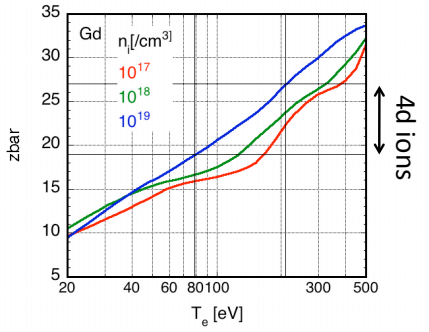
- Wavelength decreases as atomic number increases.
- Calculated spectra from 4d open shell ions from Sn to Gd look similar.





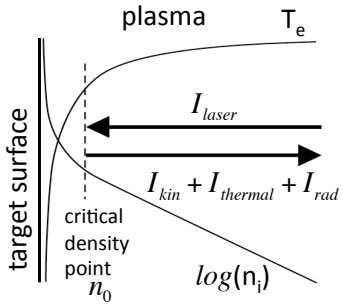
Calculation of CR (collisional radiative) model

- Coefficients of radiative transfer are calculated using level population and by applying detailed spectral profile of resonance and satellite lines.
- 4d ions of Gd is obtained in the T_e range of 80 – 200eV at the typical density of $n_i=10^{19}/cm^3$.



Estimation of CE using power balance model

- Self-similar profile of plasma is sustained by a balance of incoming laser power and outgoing thermal, kinetic and radiative power at the critical density point.



$$I_{laser} = I_{kin} + I_{thermal} + I_{rad}$$

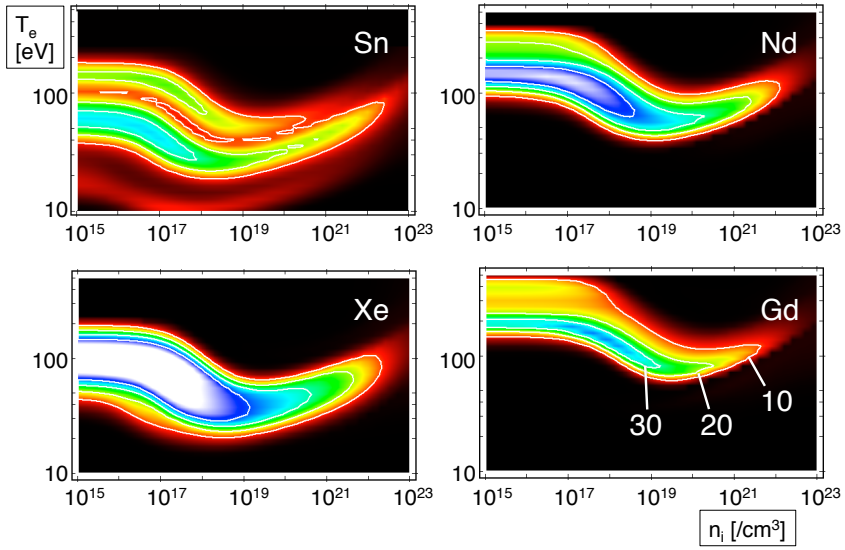
$$I_{rad} = \iint j_\nu\left(n_i(x), T_e\right) \times \exp\left[-\int_x^\infty \kappa_\nu\left(n_i(x'), T_e\right)dx'\right]dx d\nu$$

$$n_i(x) = n_0 \exp\left(-\frac{x}{c_s t}\right), \quad c_s = \sqrt{\frac{zkT_e}{M_i}}$$

$$CE = \frac{I_{EUV}}{I_{kin} + I_{thermal} + I_{rad}}$$

K. Nishihara, et al., Phys. Plasmas **15**, 056708 (2008)

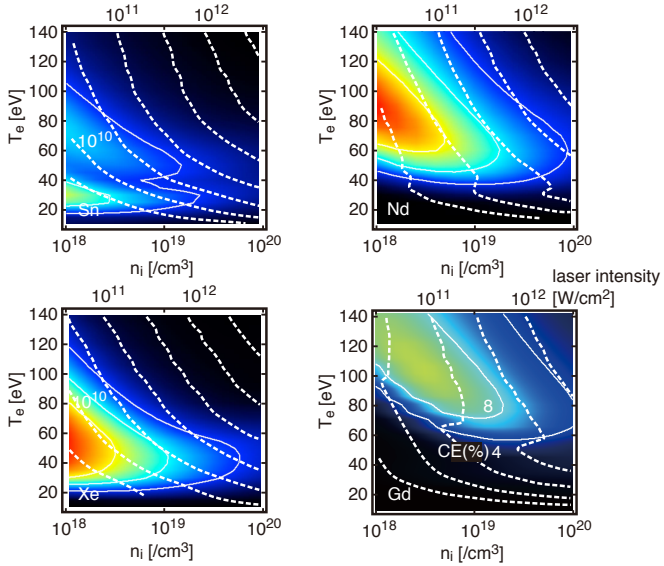
Spectral efficiency of Sn, Xe, Nd and Gd



Optimization of pumping conditions

- Radiative power loss is calculated using emissivity and opacity, taking absorption of radiation in the plasma into account.
- Emission spectrum can also been calculated.
- Laser intensity is determined from the radiative power loss, which is calculated from initial density n_0, temperature T_e, and pulse duration τ. At each n_0 and T_e, optimum pulse duration can be determined.

Optimum point shifts towards higher T_e and n_i

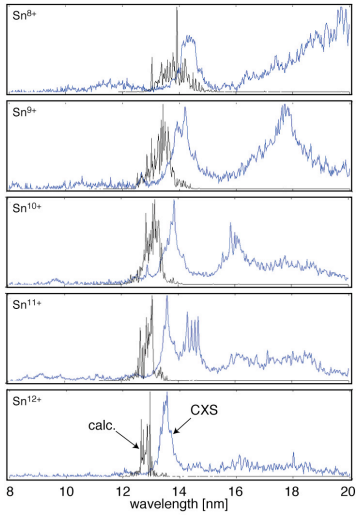


Discussion on the result of Gd and Tb sources

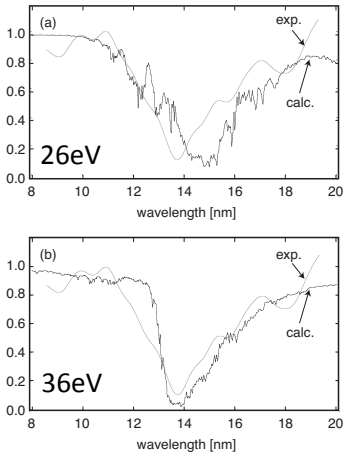
- Calculation shows EUV sources based on 4d-4f + 4p-4d transition array can be scalable to λ=65Å, using the similar atomic structure of 4d open shell ions.
- As expected from Planck's law, half the emission wavelength results in 10 times increase of pumping power from Sn sources.
- Much higher pumping power ($10^{11\text{-}12}$W/cm^2) and short wavelength (λ=1μm) for Gd and Tb sources demands innovation in the laser technology.

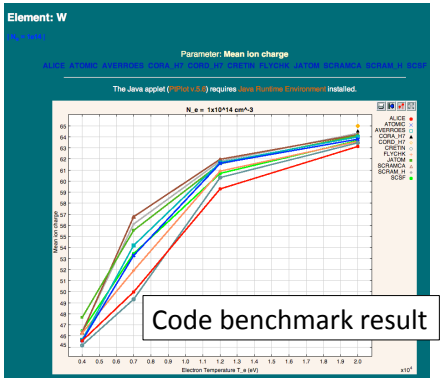
Subjects of atomic codes

- Calculated wavelength differs from experiment due to the effect of CI.
- Calculation including CI is impossible for 4f open shell ions with any existing atomic codes.
  - ☞ Development of new atomic code is necessary.
- Identification of emission lines is very difficult for complex spectrum.
  - ☞ Machine learning algorithms help spectroscopy.



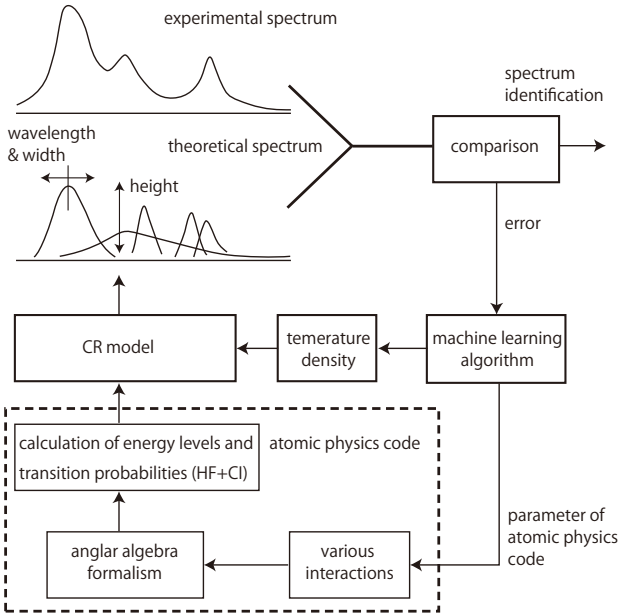
- Agreement between calc. and exp. sometime occurs at more than one conditions, making determination of T_e and n_i difficult.
- Result from each code is different depending on the atomic model and rate coefficients.





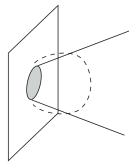
Sn n_i=8x10^{20}/cm^3

A. Sasaki, et al. J. Appl. Phys.107, 113303(2010)

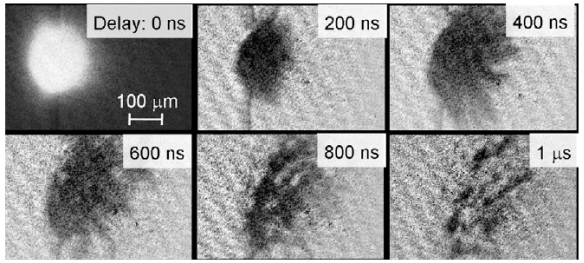


Subjects of radiation hydrodynamics simulation (2)

- Initial laser and target interaction sometimes creates non-uniform structure in the plasma, which is difficult to calculate.
- Mechanism of non-uniform ablation is also important for debris formation and development of the method of mitigation.

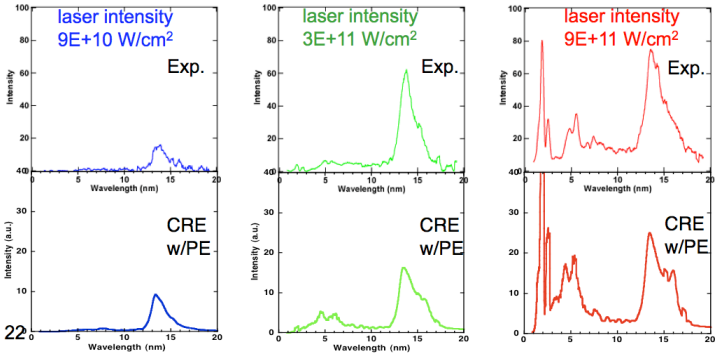


D. Nakamura, et al., J. Phys. D: Appl. Phys. **41** (2008) 245210



Subjects of radiation hydrodynamics simulation (1)

- As the optical thickness of the plasma increases, difference between calculation and experiment.
- Coupled hydrodynamics, atomic process, and radiation transport is difficult to calculate.



Summary

For the development of short wavelength light sources, not only laser technology theoretical methods will also be useful.

- To overcome difficulty to produce high temperature plasmas.
- To find new atomic transitions which have strong emission in the λ=6.5nm region.

Subjects:

Development of a new atomic code.

Development of new methods to calculate non-uniform structure and radiation transport in plasmas.